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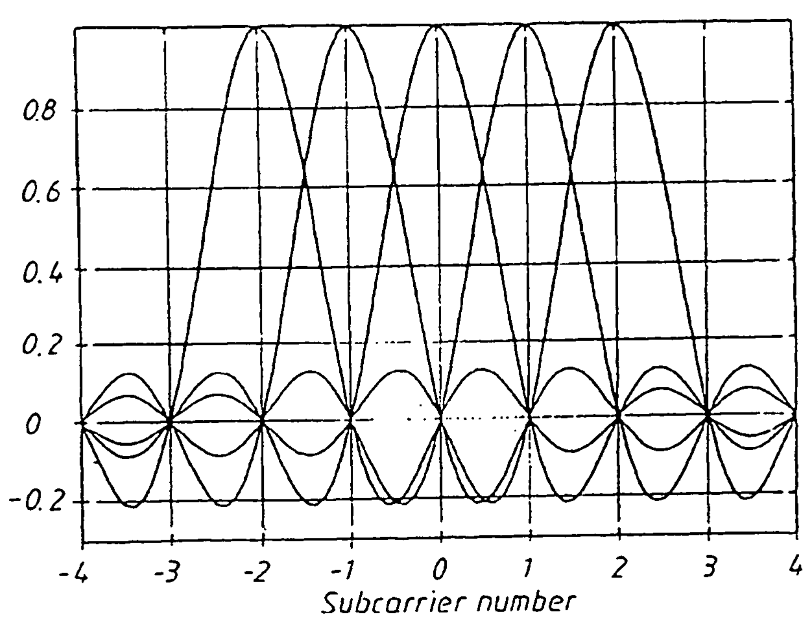
(54) Pulse shaping for multicarrier systems

(57) The present invention is a method of increasing the maximum available bit rate on a single data link, in order to gain capacity within single cells. The method uses the fact that the pulse shaping introduces known inter symbol interference (ISI) and utilises the idea of overcoming ISI by equalization.

Fig-1



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Description

The present invention relates to an orthogonal frequency division multiplex system, employing pulse shaping and having an enhanced available bit rate, and a method of increasing the available bit rate in a pulse shaped orthogonal frequency division multiplex system.

One of the key issues when designing a third generation multiple access system is the need to support high bit rates, see for example P Willars, "Key Issues for a 3rd Generation Multiple Access Concept", WW3/BAI/95/070. In a multiple access system based on OFDM, the signal has to be pulse shaped in order to suppress the side lobes and reduce the size of the neighbouring guard bands. Unfortunately, pulse shaping breaks orthogonality on every other sub-carrier and reduces the available bit rate (on a link level) by a factor two. The present invention enables recovery of the lost orthogonality thus making it possible to transmit data with the full bit rate and suppressed side lobes. This results in only a slight loss in performance.

Where there is a demand for high bit rates, this will reduce system capacity (in terms of the number of users per cell). If the system capacity is to be increased there will be a need for increases in infrastructure investment, see C. Ostberg "Coupling Losses, Coverage Range and Spectrum Mask Requirements", WW3/BAI/95/071. Therefore, it is very important for OFDM systems to support high maximum and highly variable bit rates in a single cell. In comparison with other transmission technologies, OFDM systems demonstrate that they can support the highest bit rates, see for example P Willars "A Comparison of Multiple Access Concepts", WW3/BAI/95/049.

The present invention is a method of increasing the maximum available bit rate on a single data link, in order to gain capacity within single cells. The method uses the fact that the pulse shaping introduces known inter symbol interference. The invention uses the idea of overcoming ISI by equalization.

According to a first aspect of the present invention, there is provided an OFDM system, comprising a transmitter and a receiver, in which side lobes are suppressed by pulse shaping, characterised in that loss of carrier orthogonality induced by pulse shaping is compensated by an equaliser located in the receiver.

Said equaliser may be a predictive equaliser.

Said equaliser may be a MLSE equaliser.

An estimated data sequence $X_{est,k}$, may be selected such that the metrics $(Z_k-(X_{est,k}\otimes W_k))^2$ are minimised.

Said metrics may be calculated by means of a Viterbi algorithm, in a Viterbi decoder.

A total of $N \cdot M^{K-1}$ metrics may be calculated, where X_k belongs to a M symbol alphabet, said OFDM system transmits N sub-carriers and said filter length is K.

K may be equal to 3.

A radio interface may be transmitted over non-adjacent sub-carriers.

Said pulse shaping may be produced by combining a modulated data signal with a window function prior to transmission.

Said window function may be a Hanning window function.

Data may be modulated onto sub-carriers using differential quadrature phase shift modulation.

Data may be modulated onto sub-carriers using binary phase shift keying.

According to a second aspect of the present invention, there is provided an OFDM receiver adapted to receive an OFDM signal in which side lobes are suppressed by pulse shaping, characterised in that said receiver includes an equaliser adapted to compensate for a loss of carrier orthogonality induced by pulse shaping.

According to a third aspect of the present invention, there is provided, in an OFDM system in which side lobes are suppressed by pulse shaping, said system including a transmitter and a receiver, a method of compensating for loss of orthogonality induced in a transmitted OFDM signal by pulse shaping characterised by equalising a received pulse shaped OFDM signal at said receiver.

Said equalising may be predictive equalising.

Said equalising may be performed by a MLSE equaliser.

Said equalisation process may include the step of selecting an estimated data sequence $X_{est,k}$, such that the metrics $(Z_k-(X_{est,k}\otimes W_k))^2$ are minimised.

Embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 shows the relationship between different sub-carriers in an OFDM system.

Figure 2 illustrates, in schematic form, pulse shaping in an OFDM transmitter.

Figure 3 shows the result of pulse shaping sub-carriers with a Hanning window.

Figure 4 shows a performance comparison in an OFDM system of cyclic prefix and pulse shaping.

Figure 5 illustrates, in schematic form, an OFDM system according to the present invention.

Figure 6 illustrates the performance advantages of the present invention.

To facilitate an understanding of the present invention, a glossary of some of the abbreviations used in this patent specification are set out below.

BPSK: Binary Phase Shift Keying.

DFT. Discrete Fourier Transform.

DQPSK Differential Quadrature Phase Shift Keying.

FFT Fast Fourier Transform.

IFFT Inverse Fast Fourier Transform.

ISI Inter Symbol Interference.

MLSE A predictive equaliser in which the most probable data sequence is estimated by comparing an estimated data sequence which has been subjected to a similar distortion as the original data sequence with the original data sequence.

OFDM Orthogonal Frequency Division Multiplex.

QPSK Quadrature Phase Shift Keying.

SNR Signal to Noise Ratio.

In OFDM the fundamental part of the modulation/demodulation process is performed by means of a Discrete Fourier Transform (DFT). The DFT can be calculated using an efficient algorithm, such as the Fast Fourier Transform (FFT) algorithm. The fundamental properties of the transform introduces block processing, where the data is divided in successive blocks, which causes the sub-carriers to widen into Sinc-functions, (i.e. $F(x)=\sin(x)/x$), in the frequency plane. This is illustrated in Figure 1. The sub-carrier maxima are located at the zero-crossings of adjacent sub-carriers. For this reason the system is said to be orthogonal.

The slow decay of the sub-carrier Sinc-function (~1/f), requires the introduction of large guard bands in order to suppress interference with adjacent frequency bands.

To reduce the guard bands, it has been proposed that, in an OFDM system, the signal should be shaped using an appropriate window function, such as a Hanning window, before transmission, see B. Engström, "A Class of OFDM Pulse Shapes" WW3/BAI/9/020 and M. Gudmundsson, "RF Considerations of OFDM Signals", WW3/BAI/95/047. The signal is multiplied with the window function as shown in Figure 2. The incoming modulated data, X_k, is subjected to FFT processing to produce a signal x_n. This signal is then multiplied by a Hanning window function, w_n, to produce a signal y_n which is transmitted. As explained later, the transmitted signal, y_n, has suppressed side lobes.

The Hanning window function is defined as:

$$w(n) = \begin{cases} 1-\cos\left(\frac{2\pi n}{N}\right) & 0 \le n < N-1 \\ w(n+pN) & p=\pm 1, \pm 2 \ldots\ldots \end{cases} \qquad (1)$$

where n is the time index and N is the block size of the FFT.

In order to examine the effect of the window function on the data, the system is transformed into the frequency domain. The window function is cyclic with a periodicity of N, and its Fourier transform is written as:

$$W_k=\delta(k) - \frac{1}{2}\delta(k-1) - \frac{1}{2}\delta(k+1) \qquad (2)$$

where δ(k) is the Kronecker delta function and k is the Fourier series coefficient (and sub-carrier number). The multiplication in the time domain is equivalent to a convolution in the frequency domain, and the signal, Y_k, is written as:

$$Y_k=X_k \otimes W_k=\sum_{l=0}^{N-1} X_{k-l} \cdot W_l = X_k - \frac{1}{2}X_{k-1} - \frac{1}{2}X_{k+1} \qquad (3)$$

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where the ⊗ symbol represents cyclic convolution.

This pulse shaping method results in the sub-carrier plot illustrated in Figure 3. The pulse shape decays in proportion to 1/f. It can easily be seen from equation (3), and Figure 3, that orthogonality is lost on every other sub-carrier and that the pulse shaping reduces the maximum available bit rate, on a single data link, by a factor two. This means that only alternate sub-carriers can be used for data transmission. The system capacity is not, however, reduced by the same amount, because significantly smaller guard bands can be used, see M Gudmundsson and P. O. Anderson. "WW£/BAI/OFDM First results on transmission studies", WW3/BAI/94/002, pA1.

Two important aspects of performance are the signal energy per sub-carrier, Eb/N0 and Signal to Noise Ratio (SNR). The physical meaning of these parameters is complicated where pulse shaping is used, because, only half the data rate can be utilized for transmission, thus reducing data transfer by a factor two. On the other hand, half of the noise energy is also lost in the receiver. This means that performance is not degraded in terms of both a SNR and Eb/NO.

Because the sub-carrier is widened by the pulse shaping, there will be some loss of performance, since the terminal has a fixed output power. Pulse shaping does not necessarily change the energy of the signal. This implies a need for a normalization of the pulse shaping filter. The normalization factor can be calculated from the following equation:

$$\Sigma a^2 . W_k^2 = 1 \tag{4}$$

where a is the normalization factor, and is given by:

$$a = \sqrt{\frac{1}{\Sigma W_k^2}} \tag{5}$$

Using W_k from (2) gives:

$$a = \sqrt{\frac{2}{3}} \approx -0.88 db \tag{6}$$

This means that pulse shaping gives a performance loss of 0.88 dB, in an AWGN-channel, compared to the theoretical performance.

If a cyclic prefix is used, the performance loss is proportional to the size of the cyclic prefix-symbol length ratio. This is because the cyclic prefix is removed and thrown away in the receiver. If the cyclic prefix is, for example, 10% of the total symbol length, the performance loss is:

$$10.\log (1.10) \approx 0.95 dB \tag{7}$$

An important question is whether it is possible to transmit on all sub-carriers without loss in performance. Apparently, transmission on all sub-carriers will cause loss of orthogonality, but in a very controlled way from which it might be possible to recover.

Examining equation (3), it can be seen that the pulse shaping of the signal x_n, can also be viewed as a time dispersive channel introducing inter symbol interference (ISI) on the same signal in the frequency domain X_k. Ordinary methods of combating ISI can, therefore, be used to correct for the loss of orthogonality introduced by pulse shaping. Note that the filter taps are static and known, which significantly reduces the problem. An equivalent model for the OFDM system, implemented in the frequency domain, is illustrated in figure 5.

On the assumption that it is possible to equalize the channel, the detection problem is the same as in the time domain, except for the cyclic convolution in the pulse shaping filter. The cyclic convolution is, however, a minor problem which can be avoided by building in the appropriate data, relating to the cyclic convolution, into the decoder. Thus, a relatively minor and simple modification will allow transmission on all sub-carriers.

Several different approaches can be used for detection of the data sequence. One possible approach to the problem is to pre-distort data before the pulse shaping filter, or perform an inverse filtering in the receiver, so that the data will be correctly detected in the receiver. Unfortunately, both these methods regenerate the problems which pulse shaping is intended to solve, namely:

- reduction of the guard bands; and

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- suppression of ISI between OFDM-symbols.

It is much better to use predictive equalisation to estimate the transmitted information in an intelligent manner. This can be done with a MLSE-equalizer.

A MLSE-equalizer chooses the most probable data sequence, by comparing the received data signal with a reference data signal which has been distorted in the same way as the received data. The optimum way of detecting the data is to choose the data sequence $X_{est,k}$, that minimizes the metrics:

$$\min\left(Z_k-(X_{est,k}\otimes W_k)\right)^2) \qquad (8)$$

with the same signal names as in Figure 5. If X_k belongs to an M symbol alphabet and transmission is on N sub-carriers, M^N metrics must be calculated in order to find the most probable data sequence. Knowing that N is a large number (1024 in the OFDM system used in the present invention), the direct calculations cannot be performed. The Viterbi algorithm is, however, a computationally efficient method, optimized for this kind of problem. With the Viterbi decoder, the necessary calculations are reduced to $N.M^{k-1}$ where K is the filter length (in the case of the present invention K=3).

The ISI introduced by the pulse shaping window, will degrade the performance on the data transmission. There is, however, a trade-off between the performance loss in SNR against the gain in transmission rate. The strong connections between the sub-carriers implies that the errors will be bursty, thus if there is an error on one sub-carrier, it is likely that the surrounding sub-carriers will also be corrupted. This is important to remember when designing the whole system. In order to be able to correct errors for a specific service, the radio interface should, if possible, use non-adjacent sub-carriers.

The expected performance of a MLSE equalizer is evaluated in "Digital Communications" by J.G. Proakis, Published McGraw Hill 1989. Following the calculations in section 6.7.1, on page 616, of this reference, define:

$$F(z)=f_{-1}.z^{-1}+f_0+f_1.z^1 \qquad (9)$$

which is a time dispersive channel. Next assume some symbol errors of length 2n-1 and define the error polynomial:

$$\varepsilon(z)=\sum_{k=-(n-1)}^{n-1}\varepsilon_k z^k \qquad (10)$$

The only thing that it is necessary to know about the errors is that the first and last terms in the sum are not equal to zero. The polynomial can now be defined as:

$$\alpha(z)=F(z).\varepsilon(z) \qquad (11)$$

and

$$\delta^2=\sum_i \alpha_i^2 \qquad (12)$$

where α_i is the coefficients of the α-polynomial. It can be shown that the minimum value of δ^2 represents the upper bound of the performance loss due to ISI ("Digital Communications" by J.G. Proakis, Published McGraw Hill 1989 pp. 621). The minimum value of δ^2 corresponds to the occurrence of as few error as possible. It is, therefore, possible to rewrite equation (10) as:

$$\varepsilon(z)=\varepsilon_{-\beta}.z^{-\beta}+\varepsilon_\beta.z^\beta \qquad (13)$$

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where $\beta=n-1$. Equation (11) can now be rewritten as:

$$\alpha(z)=F(z).\varepsilon(z)=(f_{-1}.z^{-1}+f_0+f_1.z^1)\,(\varepsilon_{-\beta}.z^{-\beta}+\varepsilon_\beta.z^\beta) \tag{14}$$

The minimum value of δ^2 can now be evaluated. δ^2_{min} is bounded by the smallest and highest degree coefficients in the α-polynomial. This is because they only appear once and do not interact with any other terms. δ^2_{min} is written as:

$$\delta^2_{min}=(f\text{-}1.\varepsilon_{-\beta})^2+(f_1.\varepsilon_\beta)^2=(-\frac{1}{2})^2+(-\frac{1}{2})^2=\frac{1}{2}=-3dB \tag{15}$$

The upper bound of the performance loss is 3 dB. Knowing that the calculated upper bound is the worst possible case it might therefore, be expected that there will be no severe performance losses compared to the 0.88 dB loss calculated above.

In order to verify the calculations set out above, a simulation model was built. The simulation used BPSK-modulation. In practice, a system would use a higher modulation form such as (DQPSK). Therefore, the results of the simulation cannot be mapped to a practical system.

Figure 6 shows that for a bit error rate of 10^{-3}, the loss is approximately 1 dB, which seems to be a negligible amount compared to the gain in transmission rate. For lower bit error rates (such as 10^{-6}) the performance loss is even smaller.

The performance for all SNR-values is under the 3 dB bound, as expected. The largest performance loss is almost 3 dB for a bit error rate of $\sim 10^{-1}$, which is in a non-usable area for data transmission.

The present invention describes a method for transmitting data on all sub-carriers in an OFDM system when the side lobes are suppressed with a Hanning window. The method is based on the concept of controlling Inter Symbol Interference by using a MLSE-equalizer in the receiver. The calculations and simulations show a small performance loss for BPSK which seems to be negligible. For lower bit error rates the performance loss is even smaller.

Claims

1. An OFDM system comprising a transmitter and a receiver, in which side lobes are suppressed by pulse shaping, characterised in that loss of carrier orthogonality induced by pulse shaping is compensated by an equaliser located in the receiver.

2. An OFDM system as claimed in claim 1, characterised in that said equaliser is a predictive equaliser.

3. An OFDM system as claimed in claim 2, characterised in that said equaliser is a MLSE equaliser.

4. An OFDM system as claimed in either claim 2, or 3, characterised in that an estimated data sequence $X_{est,k}$, is selected such that the metrics $(Z_k\text{-}(X_{est,k}\otimes W_k))^2$ are minimised.

5. An OFDM system as claimed in claim 4, characterised in that said metrics are calculated by means of a Viterbi algorithm, in a Viterbi decoder.

6. An OFDM system as claimed in claim 5, characterised in that a total of $N.M^{k-1}$ metrics are calculated, where X_k belongs to a M symbol alphabet, said OFDM system transmits N sub-carriers and said filter length is K.

7. An OFDM system as claimed in claim 6, characterised in that K = 3.

8. An OFDM system as claimed in any previous claim, characterised in that a radio interface is transmitted over non-adjacent sub-carriers.

9. An OFDM system as claimed in any previous claim, characterised in that said pulse shaping is produced by combining a modulated data signal with a window function prior to transmission.

10. An OFDM system as claimed in claim 9, characterised in that said window function is a Hanning window function.

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11. An OFDM system as claimed in any previous claim, characterised in that data is modulated onto sub-carriers using differential quadrature phase shift modulation.

12. An OFDM system as claimed in any of claims 1 to 10, characterised in that data is modulated onto sub-carriers using binary phase shift keying.

13. An OFDM receiver adapted to receive an OFDM signal in which side lobes are suppressed by pulse shaping, characterised in that said receiver includes an equaliser adapted to compensate for a loss of carrier orthogonality induced by pulse shaping.

14. An OFDM receiver as claimed in claim' 13, characterised in that said equaliser is a predictive equaliser.

15. An OFDM receiver as claimed in claim 14, characterised in that said equaliser is a MLSE equaliser.

16. An OFDM receiver as claimed in either claim 14, or 15, characterised in that an estimated data sequence $X_{est.k}$, is selected such that the metrics $(Z_k-(X_{est.k}\otimes W_k))^2$ are minimised.

17. An OFDM receiver as claimed in claim 16, characterised in that said metrics are calculated by means of a Viterbi algorithm, in a Viterbi decoder.

18. An OFDM receiver as claimed in claim 16, characterised in that a total of $N.M^{k-1}$ metrics are calculated, where X_k belongs to a M symbol alphabet, said OFDM system transmits N sub-carriers and said filter length is K.

19. An OFDM receiver as claimed in claim 18, characterised in that K = 3.

20. In an OFDM system in which side lobes are suppressed by pulse shaping, said system including a transmitter and a receiver, a method of compensating for loss of orthogonality induced in a transmitted OFDM signal by pulse shaping characterised by equalising a received pulse shaped OFDM signal at said receiver.

21. A method as claimed in claim 20, characterised in that said equalising is predictive equalising.

22. A method. as claimed in claim 21, characterised in that said equalising is performed by a MLSE equaliser.

23. A method. as claimed in either claim 21, or 22, characterised in that said equalisation process includes the step of selecting an estimated data sequence $X_{est.k}$, such that the metrics $(Z_k-(X_{est.k}\otimes W_k))^2$ are minimised.

24. A method, as claimed in claim 23, characterised in that said metrics are calculated by means of a Viterbi algorithm, in a Viterbi decoder.

25. A method. as claimed in claim 24, characterised in that a total of $N.M^{k-1}$ metrics are calculated, where X_k belongs to a M symbol alphabet, said OFDM system transmits N sub-carriers and said filter length is K.

26. A method. as claimed in claim 25, characterised in that K = 3.

27. A method, as claimed in any of claims 20 to 26, characterised in that a radio interface is transmitted over non-adjacent sub-carriers.

28. A method, as claimed in any of claims 20 to 27, characterised in that said pulse shaping is produced by combining a modulated data signal with a window function prior to transmission.

29. A method, as claimed in of claims 20 to 28, characterised in that said window function is a Hanning window function.

30. A method, as claimed in any of claims 20 to 29, characterised in that data is modulated onto sub-carriers using differential quadrature phase shift modulation.

31. A method, as claimed in any of claims 20 to 29, characterised in that data is modulated onto sub-carriers using binary phase shift keying.

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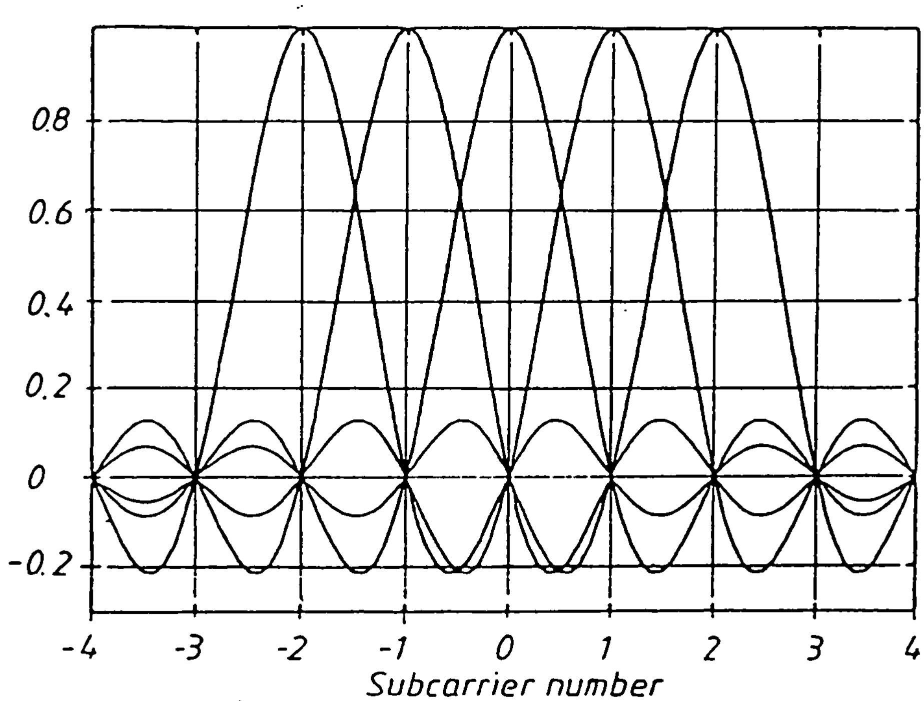
Fig. 1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0.4
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-0.2
-4
-3
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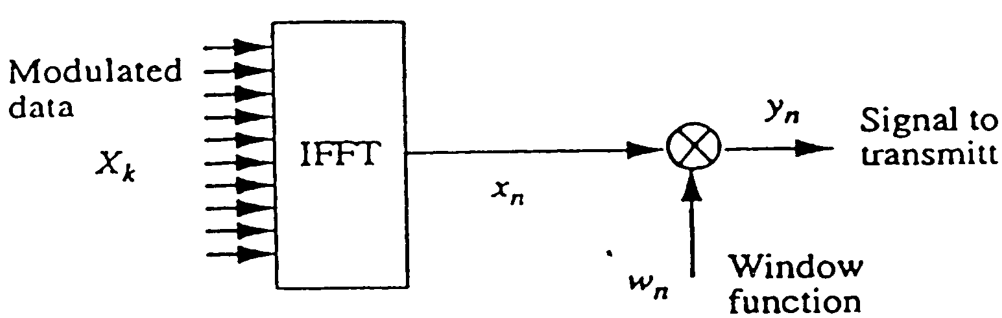
-1
0
1
2
3
4
Subcarrier number

Fig. 2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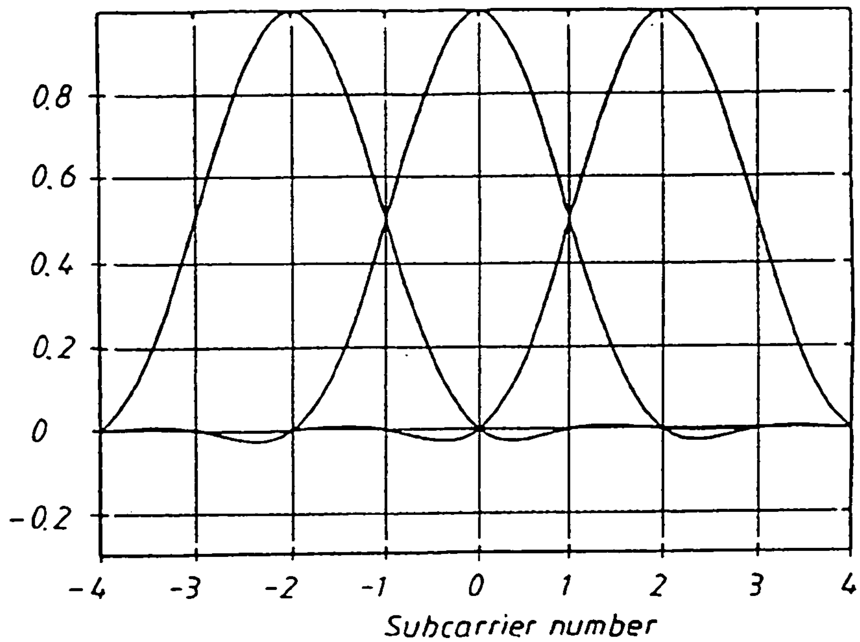
X_k
IFFT
x_n
y_n
Signal to transmitt
w_n
Window function

Fig. 3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0.6
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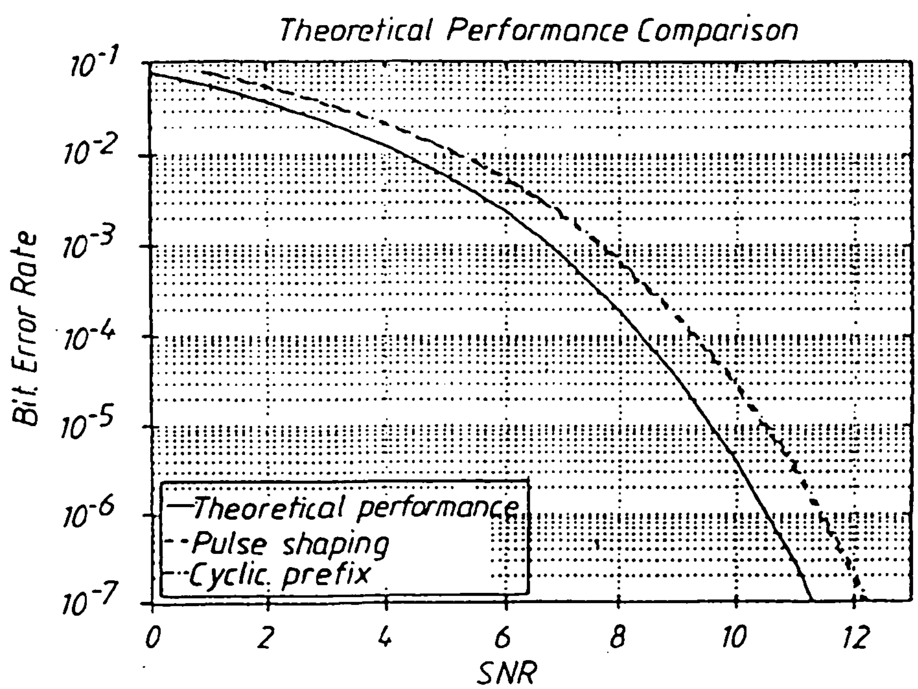
3
4
Subcarrier number

Fig. 4


Theoretical Performance Comparison
Bit. Error Rate
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
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- -Pulse shaping
-·-Cyclic. prefix
0
2
4
6
8
10
12
SNR

Fig. 5

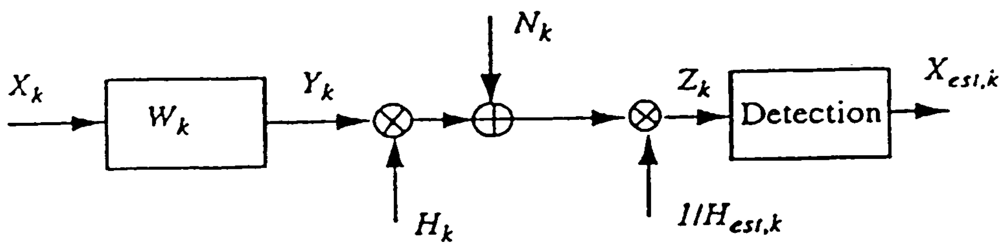
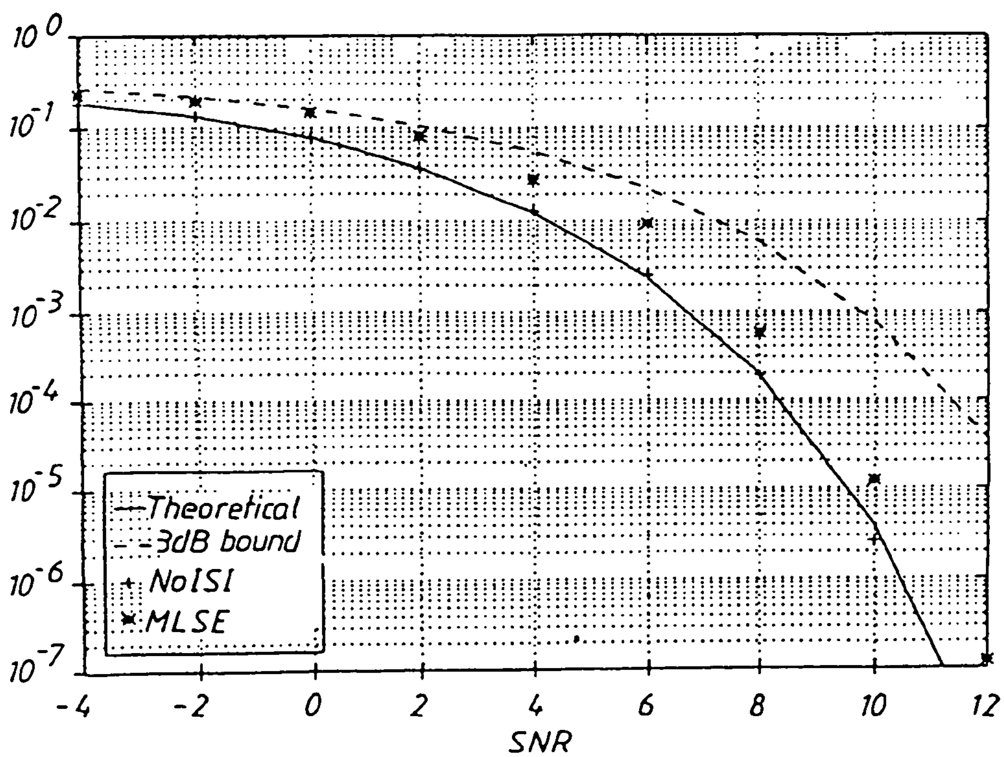

X_k
W_k
Y_k
N_k
H_k
Z_k
$1/H_{est,k}$
Detection
$X_{est,k}$

Fig. 6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10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Theoretical
3dB bound
NoISI
MLSE
-4
-2
0
2
4
6
8
10
12
SNR

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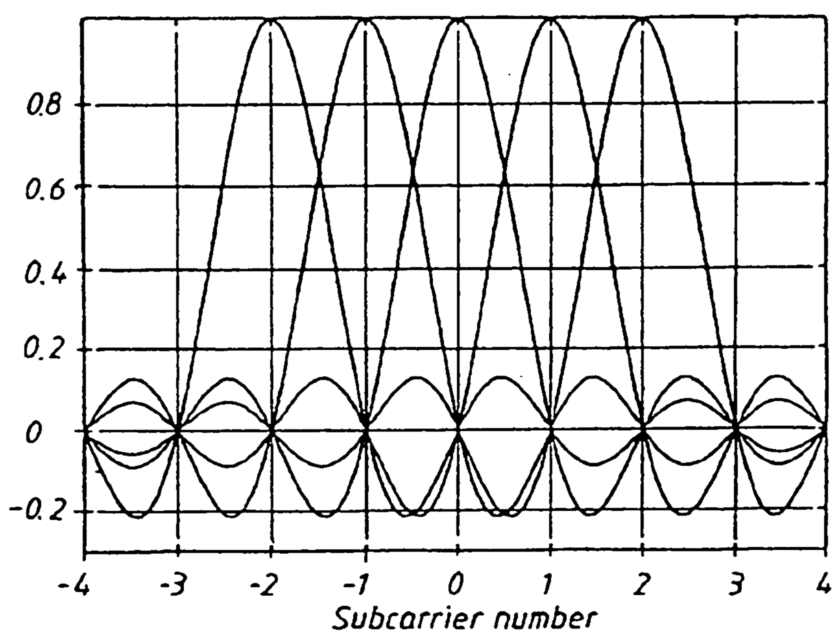
Fig.1



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EUROPEAN SEARCH REPORT

Application Number
EP 97 85 0081

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
X	FR 2 680 061 A (THOMSON CSF) 5 February 1993 (1993-02-05) * page 4, line 18 - line 19 * * page 4, line 26 - line 29 * * page 5, line 23 - page 6, line 2 * * page 7, line 25 - line 28 *	1,12,13, 20,31	H04L27/26 H04L25/03
Y	* figures 1,2 *	2-5, 9-11, 14-17, 21-24, 28-30	
Y	US 5 285 474 A (CHOW JACKY ET AL) 8 February 1994 (1994-02-08) * abstract * * column 10, line 16 - line 26 * * figures 2B,2C *	2,3,14, 15,21,22	
Y	US 4 881 241 A (ALARD MICHEL ET AL) 14 November 1989 (1989-11-14) * column 3, line 12 - line 20 * * column 5, line 19 - line 30 * * column 6, line 6 - line 11 * * column 10, line 41 - line 45 * * figure 4 *	2,4,5, 11,14, 16,17, 21,23, 24,30	TECHNICAL FIELDS SEARCHED (Int.Cl.6) H04L

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
BERLIN	7 December 2000	Farese, L

CATEGORY OF CITED DOCUMENTS

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DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
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Y	US 5 345 440 A (ANIKHINDI SANTOSH V ET AL) 6 September 1994 (1994-09-06) * column 6, line 43 - line 65 * * figures 2A,2B *	11,30	
X	US 5 416 767 A (KOPPELAAR ARIE G C ET AL) 16 May 1995 (1995-05-16) * abstract * * column 2, line 42 - line 47 * * column 3, line 21 - line 30 * * column 4, line 5 - line 20 * * column 6, line 2 - line 9; figures 1,6 *	1,8	
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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
BERLIN	7 December 2000	Farese, L

CATEGORY OF CITED DOCUMENTS

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